CALIFORNIA INSTITUTE OF TECHNOLOGY

EARTHQUAKE ENGINEERING RESEARCH LABORATORY

VIBRATION TESTS OF THE ENCINO DAM INTAKE TOWER

by

W. O. Keightley, G. W. Housner, and D. E. Hudson

A report of research carried out by the Earthquake Engineering Research Institute under State of California Standard Agreement No. 2163, for the State of California, Department of Public Works, Division of Architecture, Anson Boyd, State Architect.

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Summary of Conclusions

1. Field handling and installation characteristics of the newly developed mechanical vibration exciter were completely satisfactory under unusually severe conditions of application.
2. The mechanical operation of the new vibration exciter was entirely satisfactory, and no significant design changes were indicated. An important advantage of the new shaker is the fact that a relatively pure sine wave force is generated, with a very low harmonic content. This makes it possible to use accelerometer type transducers for structural motion measurements, without the appearance of disturbing high-frequency noise on the records.
3. The electric drive and control system operated with outstanding success. The portability and ease of handling of the equipment under adverse field conditions was satisfactory, and the stability of speed control was excellent. It appeared during the tests that a finer speed control would be desirable, and subsequently the speed control knob was replaced by a vernier control which has improved this feature.
4. The frequencies of the first two modes of vibration of the tower could be accurately determined by measuring wind-excited vibrations with a sensitive seismograph mounted at the top of the tower. These measured frequencies correlated well with the calculated frequencies and with the frequencies experimentally determined in the forced vibration tests.

5. Digital computer calculations using standard techniques of vibration analysis are well adapted to the analytical determination of natural frequencies and mode shapes of tower-like structures. A good correlation between analytical and experimental determinations can be expected if knowledge of the dynamic properties of the construction materials is available.
6. The stability of the mechanical vibration exciter and its speed control system is such that accurately defined resonance curves can be obtained over the complete range for structures having damping at least as low as 2 percent of critical damping.
7. Pronounced non-linear effects were encountered in the tower structure even though the maximum stresses were only of the order of 100 lb/in^2. The downward shift of resonant frequency with increased load level indicates a soft type of non-linear restoring force curve, as would be expected for concrete.
8. The amount of damping in the tower at the low compressive stresses involved in the test was determined to be from 2 to 3 percent of critical damping. The damping increased with higher load levels as would be expected. This value of damping is somewhat lower than might have been anticipated, which is probably accounted for by the low stress levels of the test, the monolithic nature of the structure, and the fact that the dynamic stress in the concrete was at all times compressive.
9. An appreciable amount of the amplitude of vibration of the top of the tower can be ascribed to deformations in the foundation

system which lead to a rotation about the base. It is interesting to note that even though the foundation is established on firm rock, these deformation effects are not negligible.

1. Introduction. The need for dynamic tests of full size structures has been realized for many years. The only way in which the parameters of major interest in structural dynamics problems, such as effective dynamic spring constants, energy dissipation characteristics, etc., can be determined, is by tests of actual structures under relatively high loading conditions. Such tests have very seldom been possible because of (1) the difficulty of applying dynamic loads of the required type and magnitude; (2) the difficulty of making the required measurements of dynamic structural responses; and (3) the unavailability of suitable test structures which could be loaded to the point of significant damage.

Because of the potential importance of dynamic tests for earthquake resistant design, the California State Department of Architecture is sponsoring through the Earthquake Engineering Research Institute the development of a large scale vibration exciter system suitable for tests of full-size structures. Work on this system, which is being developed at the California Institute of Technology, has been going on for the past two years. The complete vibration exciter system is ultimately to consist of four separate rotating-weight type mechanical vibration exciter units which can be operated simultaneously and synchronized to excite various modes of vibration.

With the completion and laboratory test of the first unit of vibration exciter and associated electrical drive and control system late in 1960, it was felt that some important test work could be done with the single machine, and accordingly an effort was made to locate suitable test structures.

It fortunately occurred that just at this same time an opportunity appeared to make such dynamic tests on a structure which was in many respects ideal for the purpose. When the City of Los Angeles undertook a program of increasing the storage capacity of the Encino Dam reservoir by raising the height of the earth dam, it became necessary to replace the existing intake tower by a taller structure in a different location. When the reservoir was empty the Department of Water and Power offered to make the old tower available for testing prior to demolition.

The objectives of the tests were twofold. The first objective was to obtain experimental measurements from which the natural period of vibration of the tower at various stress levels could be determined, and from which the damping or energy dissipation characteristics of the structure could be calculated. The effects of foundation yielding on the vibrations of the tower were also of general interest. The second objective was to make a field trial of the newly completed large vibration exciter, which had so far been tested only in the laboratory.

The field conditions under which the tower tests were conducted were considerably more severe than had been contemplated for typical applications of the equipment, and hence constituted a very useful check of the overall effectiveness of the system. Because of this special interest in the operation of the equipment, a number of details of the actual installation and field conditions will be included in this present report.

2. The Intake Tower. The photograph of Fig. 1 will give a general impression of the old Encino Dam intake tower before demolition. The sketch of Fig. 2 will indicate the significant dimensions and structural details. The tower was a concrete cylinder 17' - 0" in outside diameter, and 114' - 7" in height, with four different wall thickness sections decreasing from the base. The simple form of the structure made it an ideal subject for vibration test studies, and offered optimum conditions for a comparison of theoretical calculations and experimental measurements.

Preliminary calculations showed that the dynamic force which could be generated by the single available vibration exciter unit would be sufficient to load the tower near the damage point at resonance. When it was learned that the tower was unreinforced except for some steel dowels into the footing and some bars in the roof slab, it was decided that the vibration of the tower during the test should be limited to the point that no tension stresses would be developed in the tower walls.

The tower was in good condition, with no visible cracks or spalls except at construction joints. The concrete had a generally sound appearance, except for a soft surface. The concrete had undoubtedly benefitted from having been cured under water for some 40 years.

Three 4-1/2 inch diameter cores were taken from the base of the tower. A static compression test on one of these cores gave an ultimate compressive strength of 4700 lb/in^2.

The dynamic modulus of elasticity of the core material was measured by vibrating the cores as free-free beams, using an Electro Products Laboratories "Sonometer". The fundamental frequency of vibration of the 4.66 in. diameter, 14.6 in. long cylinders as a free-free beam was approximately 1825 cycles per second. At a maximum bending stress level of the order of 10 lb/in^2 the dynamic modulus of elasticity of two of the cores was found to be 2.6×10^6 lb/in^2, while the third core indicated a value of 3.1×10^6 lb/in^2.

In order to investigate the foundation conditions of the tower, two bore holes were drilled at the base. It was determined that the tower was founded on a firm rock, as indicated in the foundation report included as an Appendix to the present report.

3. Test Conditions. The conditions under which the tests were made were far from ideal, and constituted a severe trial of the vibration exciter apparatus. The time schedule for the installation of instruments and equipment was limited by the planned demolition of the tower, and by other construction activities in the area. The whole region around the base of the tower was being worked on by heavy high-speed earthmoving equipment throughout the test. The top of the tower was accessible only by means of an old iron ladder in poor condition on the exterior of the tower, so that transportation of personnel and equipment to the top was a matter of considerable difficulty. The tests had to be planned to minimize the number of times that the 100 ft. climb up the ladder was required.

Fig. 3 shows one of the earthmoving machines driving by the base of the tower and will give an idea of typical test conditions. At the left two other machines are cutting down the upstream face of the old Encino Dam. The sedan at the right of the tower base is the California Institute of Technology Mechanical Engineering Laboratory car which has the recording instruments mounted in the trunk compartment. The pickup truck at the left is a C. I. T. truck with a portable gas-engine driven generator power supply for the recording instruments, and the other C. I. T. truck carries the speed control unit for the vibration exciter. Various electrical cables for the vibration exciter and the vibration pickups may be seen going up the side of the tower.

Since this was the first field test of the vibration exciter system, it was deemed unwise to have any personnel in the confined space on top of the tower when the shaking machine was operating. This meant that the operation of the vibration exciter and the recording of the tower motions had to be done from the ground some 100 ft. below and out of sight of the rotating shaker. Fig. 4 shows the speed control console in operating position at the base of the tower on the pickup truck. The whole console is mounted on a timber and rubberized hair-pad shock absorbing system, since it had to be transported over rough terrain.

The fact that the installation and operation of the vibration exciter and control system was carried out with no trouble speaks well for the general design of the equipment, and indicates that the completion of the other units of the final system should proceed along present lines.

4. <u>The Vibration Exciter.</u> The mechanical vibrator itself consists of a pair of counter-rotating eccentric weights so arranged that a rectilinear sinusoidally varying horizontal inertia force is generated. The two weights rotate about a common vertical shaft, and are driven in opposite directions by a chain-drive system.

Fig. 5 shows a completed vibration exciter unit in the laboratory, hoisted off the floor on a rope sling. In the foreground can be seen the stacks of lead weights which fit into machined compartments in the rotating circular segments. The exciter is driven by a 1-1/2 hp D. C. motor mounted on the back of the unit, which drives the eccentric weights through a timing belt and chain system. The drive motor and tachometer assembly can be dismounted from the exciter for ease of handling, transportation, and installation. Underneath the exciter unit in Fig. 5 can be seen the welded steel frame mounting bracket, which was securely fastened to the floor at the top of the tower by eight 7/8 in. bolts in expandable lead mountings. The vibration exciter itself was then bolted to this mounting bracket. In the background of Fig. 5 can be seen two additional vibration exciter units in process of construction. These units are made mainly of aluminum castings and aluminum rolled plate to keep the weight to a minimum for convenience in handling.

The horizontal force produced by the vibration exciter unit is given in the curves of Fig. 6. The curves give the unidirectional sinusoidal force amplitude at various frequencies obtained from the maximum load of lead weights, the minimum load, and the three intermediate loads used in the present test.

When the machine is fully loaded with the lead weights, a maximum force of 921 lb. is produced at a frequency of one cycle per second. The maximum force that the machine can produce is limited by strength considerations to 5000 lb. If the speed is greater than 2. 33 cycles per second, the total amount of eccentric weight must be reduced to keep the total force less than 5000 lb. With the four complete units now under construction in synchronization, a total horizontal dynamic force of 3685 lb. can be generated at one cycle per second, and a total of 20,000 lb. at speeds greater than 2.33 cycles per second.

5. The Electric Drive & Speed Control System. The requirements of the electric drive system for the vibration exciter system are particularly stringent because of the variable torques imposed on the system and the necessity to insure stability of the whole vibrating system when operating near resonance of lightly damped structures. The ability to hold an accurate speed control at and near the resonance peak requires that the speed-torque curve of the drive system be unusually flat, with essentially a constant speed maintained at relatively very large torque variations. The requirements of the speed control also require a speed variation over a relatively large speed range.

To meet these speed control requirements a D. C. motor is used along with a servo-controlled electronic amplidyne system. The general features of the system are illustrated in the schematic diagram of Fig. 7. A tachometer driven directly from the drive motor supplies a speed signal which is compared with a standard set voltage. The difference between these voltages provides an input signal to the amplidyne amplifier, which then acts on the drive motor to adjust its speed to correspond to the set speed. Fig. 4 shows the portable speed control console containing this amplidyne apparatus. The single large black knob between the two meters gives a smooth uniform stable speed adjustment over a 40 to 1 speed range.

An accurate (0.1 per cent) measure of the shaker speed is read off the digital electronic counter seen on top of the control cabinet in Fig. 4. This counter is energized by a 100 pulse per revolution permanent magnet tachometer generator mounted on the drive motor shaft. An interior view of the control console showing the amplidyne, control amplifiers, and power supplies is shown in Fig. 8.

During the tests the control console assembly remained at the base of the tower and was connected to the drive motor at the top of the tower by a 150 ft. electrical cable. Three phase 220 v. power was obtained from a 5 hp portable gas-engine driven generator supplied by the Los Angeles Department of Water and Power.

The vibration exciter drive and speed control was found to operate perfectly throughout the test. The stability of the whole system was entirely satisfactory, and it was possible to hold the speed constant at any setting, including points near and on the resonance peak. Since the low damping in the tower produced a very sharp resonance peak, an unusually severe test was provided for the whole system.

6. <u>Installation of the Vibration Exciter.</u> The vibration exciter with the drive motor assembly removed was hoisted to the top of the tower by means of a hand operated winch, as shown in Fig. 9. The total weight of the unit in this state is approximately 580 lb. The drive motor assembly (approximately 100 lb.) and the lead weights (total of approximately 400 lb. for this test) were separately hoisted up in the same way. The 12 in. thick concrete tower roof slab had an 8 ft. diameter hole centered on the tower axis, making it necessary to mount the machine off center in the annular space around the central hole. Fig. 10 gives a plan of the tower roof with the direction

of the applied forces indicated. The vibration exciter was located at the particular point shown to correspond with the ladder position, which governed the locations at which vibration pickups could be attached to the exterior of the tower wall. One of the aluminum plates to which the vibration pickups were attached can be seen in Fig. 8, just to the right of the ladder half way between the man and the bottom of the picture.

Fig. 10 also shows the location of the concrete outlet pipe attached to the base of the tower. This outlet pipe was a source of assymmetry in the elastic properties of the tower. The major and minor principal axes of elasticity for bending are also shown in Fig. 10.

7. Transducer and Recording System. The motions of the tower during the resonance tests were recorded on twin sets of two-channel Brush Type BL202 Direct Ink Writing Oscillograph recorders with Model BL360 Carrier type amplifier inputs. These units, supplied by the Dynamics Laboratory of the California Institute of Technology, were fitted into the trunk compartment of the C. I. T. sedan as shown in Fig. 11. Power was supplied by a portable gas-engine driven generator mounted on a pickup truck.

The basic transducer unit used was the Miller Type 402-C Variable Reluctance Accelerometer (now available from the Consolidated Electrodynamics Corporation). The overall frequency response of the accelerometer-recording system was essentially constant from zero to 80 cycles per second.

The accelerometers were mounted to measure horizontal motions. One unit was mounted on the floor slab at the top of the tower, one was mounted on the side of the tower just below the floor slab at the top, and a third was attached half-way up the tower at the 50 ft. elevation. A total of four channels was initially available, but malfunctions in the cable system reduced the number of channels to three.

Overall calibrations of the accelerometer-amplifier-recording system were obtained by detaching the accelerometer from the mounting plate and rotating it 90° in each direction to apply a one g signal. Such calibration tests were made in the laboratory before the tests, on the site just before the runs, and just after the runs, and subsequently in the laboratory again. The amplifier attenuators were also calibrated, since the test runs were made at various acceleration magnitude levels. Considering the size of the recording and the overall consistency of the calibrations, the absolute acceleration accuracy of the tests was of the order of 5-10%. The degree of reproducibility of the resonance curves, as may be seen by a comparison of the ascending and descending portions of the curves, indicates that for any one resonance curve the relative values are considerably more accurate than the absolute accuracies indicated by a comparison of certain of the calibration runs.

The frequencies were determined to a higher degree of accuracy, since the digital counter used for speed measurement contained its own frequency standard with an accuracy of 0.1%.

In addition to the accelerometer measurements, displacement measurements were made at the base of the tower using a Sprengnether portable vibration seismograph modified for the U.S. Coast and Geodetic Survey for building vibration work. This was a three-component instrument with a vertical element of 1.5 sec. period and two horizontal elements of 2.0 sec. period. The damping of the seismic elements is 0.55 of critical, and the static magnification is either 300 or 600 times. The instrument records photographically on a 2 3/4 in. wide tape driven by an electric motor at a speed of approximately 1/2 in. per sec. This instrument was used to determine the motions of the tower base and foundation during the test, and was located at the position shown in Fig. 10.

All of the above instrumentation functioned satisfactorily throughout the tests. The instruments were not ideally suited to the job, and a considerable improvement in accuracy and in operating convenience could be expected from an instrumentation system more nearly tailored to test work of this kind. The present transducer-recorder system was, however, the best one commercially available without special development work, and served adequately for the present purpose.

The motion measurements are at present the weakest link in the chain in structural dynamic tests of the type here reported. Work is now being done at the California Institute of Technology under California State Division of Architecture sponsorship to modify some newly developed transducer-recorder systems which should greatly improve this situation.

8. Wind-Excited Tower Vibration Tests. A technique often used for the experimental determination of the natural frequencies of vibration of large buildings is to measure with a sensitive seismograph the motions excited by wind or traffic. The U.S. Coast and Geodetic Survey has recently

acquired for this purpose the specially modified Sprengnether portable seismograph described in the section on instrumentation. Prior to the forced vibration tests this portable seismograph was mounted on the top of the tower and excellent records of wind excited oscillations were obtained. Fig. 12 shows a sample of records obtained in this way, and it will be noted that two different modes of vibration were strongly excited. The fundamental mode of vibration had a measured frequency of 2.25 cyc./sec. The second mode vibration which also appears to be strongly excited at certain portions of the record has a measured frequency of 12.5 cyc./sec. The ratio of these two frequencies is 5.56, which may be compared with a ratio of the first two bending modes of vibration of a uniform cantilever beam of 6.25. When the non-uniform nature of the mass and stiffness distributions of the tower are taken into account, the theoretical ratio checks very closely the measured value, which indicates that the tower acted essentially as a cantilever beam in pure bending.

The response of the Sprengnether portable seismograph is not independent of the frequency, and the magnifications shown in Fig. 12 correspond to the two dominant frequencies being measured.

9. Calculation of Tower Frequencies. As a check on the natural frequencies to be expected during the tests, an analytical determination of the natural frequency and mode shapes of the bending vibration of the tower was made.

The method used was to divide the non-uniform tower into 100 segments, each of which had associated with it an appropriate lumped mass and lumped elastic properties. The Myklestad-Prohl method of numerical calculation of frequencies and mode shapes was used, and the calculations were carried out by means of a special program written for the Burroughs 220 Digital Computer of the California Institute of Technology Analysis Laboratory.

A major uncertainty in the analytical determination of the frequencies is the value of the modulus of elasticity to be used in the calculation. The three cores which were tested gave, as mentioned before, two different values of the modulus which is perhaps not surprising in view of the normal variations of properties that might be expected at different points in a structure of the size and age of the tower.

Assuming pure bending and a fixed base, the fundamental frequency of vibration with a modulus of elasticity of 3.1×10^6 lb/in^2 calculates to be 2.86 cyc./sec. A modulus of elasticity of 2.6×10^6 lb/in^2 would correspond to a frequency of 2.66 cyc./sec. The ratio of the frequencies of vibration of the second mode to the fundamental frequency was calculated to be 5.56, which checks exactly the ratio computed from the wind excited tests.

The above calculated frequencies would be expected to be high, because the foundation of the tower is not in fact rigid, but can deform both in translation and in rotation. As will be discussed later in connection with the resonance tests, the two fundamental frequencies corresponding to bending about the major and minor axes of the tower were approximately 2.1 cyc./sec. and 2.4 cyc./sec. These values are consistent with those obtained for the fundamental frequency by the wind-excited test, considering the facts that the wind would probably excite mostly motion about the more flexible axis, and hence would excite the lower frequency, and that the wind-excited vibrations were at a lower stress level than the forced vibration tests which might lead to somewhat higher frequencies.

Computer calculations were next made to study the effects of foundation flexibility on the natural frequencies. It was found that the introduction of sufficient base rotation flexibility to reduce the fundamental natural frequency to approximately 2.2 cyc./sec. maintained a ratio of second mode to fundamental frequency of 5.62, not far from that measured during the wind-excited test. Furthermore, this amount of rotational stiffness corresponding to this frequency shift results in a rigid body rotation of the tower of an amount to account for approximately 40% of the motion of the top of the tower in the first mode of the forced vibration test. This amount of foundation motion was consistent with the measurements made by the Sprengnether portable vibration seismograph at the base of the tower during the forced vibration tests.

It was also determined by computer studies that a base translational flexibility of an amount sufficient to reduce the fundamental frequency to 2.2 cyc./sec. would lead to a ratio of second mode frequency to fundamental frequency of 2.54, which is obviously far from correct. It can thus be concluded that the major effect of foundation compliance is equivalent to a base rotation.

10. The Forced Vibration Tests. Preliminary calculations were made to determine the magnitude of exciting force that could be permitted without setting up tension stresses in the unreinforced concrete.

The total dead weight of the tower was 1.69×10^6 lb., and the area of the base section at the foundation was 132 ft^2. This gives a direct compressive stress at the foundation of 89 lb/in^2. Calculating now the magnitude of the transverse force at the top which would set up a bending tension stress that would just cancel the direct compression, it is found that the critical section is at the midpoint of the tower height, and that the corresponding transverse force at the shaker location is 43,800 lb. This sets the maximum static force which if applied to the top of the tower would cancel the compressive stress. Based on the best information before the test as to the probable damping values of the concrete tower, a value of 7% of critical damping was assumed*. At this value of damping, the maximum dynamic amplification factor at resonance would be:

$$\frac{1}{2\left(\frac{c}{c_c}\right)} = \frac{1}{(2)(0.07)} = 7.15$$

The limiting magnitude of the equivalent exciting force during the test should not therefore exceed approximately

$$\frac{43,800}{7.15} = 6120 \text{ lb.}$$

The single available vibration exciter unit had a force generation limit of 5000 lb., set by excessive stresses in the structure of the shaking machine. It thus appeared that the full force output of the single machine would be about the proper order of magnitude for the maximum test force.

It was decided to begin the test with a considerably smaller load than this indicated maximum, and to determine resonance curves first at

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* Alford, J. L., and Housner, G. W., "A Dynamic Test of a Four-Story Reinforced Concrete Building", Bull. Seis. Soc. Amer., Vol. 43, No. 1, Jan. 1953.

relatively low load levels. This was a wise precaution, since the actual measured damping of the tower turned out to be less than half of the assumed value. This means that the maximum shaker forces would have definitely overloaded the tower.

Three different load levels were used during the tests as given in Fig. 6. The force amplitudes at one cycle per second were (1) 94 lb., (2) 230 lb., and (3) 461 lb. Considering the maximum force at the higher resonance frequency of 2.36 cycles per second, and the measured equivalent damping of 2.8 per cent of critical, the maximum dynamic force magnitude under the worst combination of conditions was:

$$(461)\left(\frac{2.36\text{ cps}}{1.00\text{ cps}}\right)^2\left[\frac{1}{(2)(0.028)}\right] = 45,900\text{ lb.}$$

This force is slightly in excess of the maximum desired force at the mid-point of the tower height. Since the applied force and the measured motions are at an angle with the axis about which the peak motion probably occurred, the above figure for maximum force should be on the high side. The bending tension stress at the base corresponding to this maximum force is:

$$\sigma = \frac{Mc}{I} = \frac{(45,900\text{ lb})(104.5\text{ ft})(8.5\text{ ft})}{\frac{\pi}{8}(8610)\text{in}^4(144)\text{in}^2/\text{ft}^2} = 83.5\text{ lb/in}^2$$

Thus the tower remained in compression by a small amount at the base for the maximum applied force condition.

The maximum measured acceleration at the top of the tower during the test was 0.043 g. This would correspond to the acceleration that might be caused by a small earthquake.

11. Resonance Curve Determinations. Resonance curves were obtained for the three loading conditions given above for measured accelerations at the top of the tower and at the midheight. The speed control was adjusted in small increments first increasing the speed from a low value to well past the resonance peaks, and then reducing speeds down through the resonance region as an additional check.

In Fig. 13 is shown a sample of the acceleration-time records obtained during these resonance tests. Note that a relatively smooth sine-wave is obtained even though an acceleration measurement is involved. This shows that the mechanical vibration exciter operates with a very satisfactory smoothness, and produces essentially a single-frequency force output. From the measured accelerations and the corresponding digital counter tachometer readings, the resonance curves of Figs. 14 and 15 were plotted.

Two pronounced resonance peaks will be observed, corresponding to vibrations about the major and minor principal elastic axes. This double peak is a consequence of the fact that the vibration exciter unit was not lined up with a principal elastic axis. It would have been preferable for the analysis of the test results to have excited only one mode of vibration, but this would have been difficult for the present test because of access limitations imposed by the position of the ladder.

The small amount of scatter of the points on the resonance curves indicates a satisfactory accuracy of acceleration measurement, and a high degree of precision in the vibration exciter controls. The fact that the resonance peaks could be so accurately defined for such small damping indicates a very satisfactory stability in the overall system.

In Fig. 16 are given computed resonance curves for a linear single degree of freedom system with viscous damping and a frequency squared excitation, which may be compared with the experimentally obtained tower resonance curves. A number of significant differences may be noted, apart from the double peak of the tower test.

It will be noted, for example, that the three resonance peaks of Fig. 14 for the different loads do not occur at the same frequency, but that the higher force levels have a distinctly lower frequency. This non-linear feature is characteristic of a force-displacement relationship which gets softer at higher forces. On the other hand, if the ratios of the accelerations at the resonance peaks are compared with the force magnitude ratios, the non-linearity might appear to be of the hardening type. It is likely, however, that this latter effect is connected rather with non-linear damping phenomena.

Another major anomaly in the data involves a comparison of the acceleration peaks at resonance at the top of the tower and at the tower midheight (Figs. 14 and 15). The midheight accelerations are considerably higher than can be explained by any possible mode shape of the tower. These tower mode shapes could not be accurately defined with the limited instrumentation at hand, although certain limiting conditions could be established. The measured values at midheight would almost seem to indicate a pure shear type of mode, although such a pure shear action would require ratios of second mode to fundamental mode which are far different from those observed. Measurements of the tower foundation rotation as mentioned above were consistent with the frequency distribution observed, but do not alter the mode shape sufficiently to explain the large values at midheight.

The amount of data at hand is not sufficient to resolve all of the above difficulties, and the destruction of the tower has made it impossible to repeat tests. The above points are interesting, however, as examples of the complex problems that arise when dealing with even the simplest structures. The experiences of the present test should in this respect be of importance in the planning and execution of future tests of this type.

12. Determination of Damping. The presence of the two resonance peaks in the curves of Figs. 14 and 15 complicates considerably the calculation of the damping in the system. Ordinary techniques based on the width of the resonance curve will not be satisfactory because of the close spacing of the peaks. After a trial comparison of several methods for damping determination, the following reasonably satisfactory procedure was evolved.

An examination of the theoretical curves for the linear single degree of freedom system of Fig. 16 shows that two of the most prominent features of these curves, for the various values of damping, are the resonance peaks themselves, and the minimum point attained above resonance, where the curves become almost horizontal. In Fig. 17 is plotted the ratio of the peak amplitude to the amplitude of this flat part of the curve, versus the damping. It will be seen that this ratio varies markedly with damping, and hence a measurement of this ratio should be a good way to calculate the damping. This method should be particularly suitable for the resonance curves of Figs. 14 and 15 since it uses primarily information on the high side of the resonance peak.

The only difficulty remaining is to sort out the effects of the two peaks. This can be done as indicated in Fig. 18.

We shall suppose that the measured resonance curves are the result of a superposition of two linear single degree of freedom curves (a) and (b). Curve (b) is considerably larger than (a) because the axis of the shaking machine is more nearly lined up with that direction than the other. As shown in Fig. 10, the inertia force from the vibration exciter makes an angle of 36 1/2 degrees with the minor elastic axis, which would directly give the response ratios about the two axes if the system were linear. These ratios cannot be expected to check out in the present case because of the pronounced non-linearity of the system.

The spacing between the two resonant peaks is, however, large enough so that at frequency ω_1 practically the whole combined curve would be curve (a). The ratios from Fig. 17 will then establish the level of curve (a) at ω_2, and this acceleration value can be subtracted from the total to give curve (b) alone. Returning to Fig. 17 will then permit a determination of the damping corresponding to the average accelerations of curve (b).

To carry out the above procedure accurately would evidently involve an iterative process. One would first assume a damping, and then compute a corrected value. In making the corrections it must be kept in mind that the damping is greater at the higher stress levels than at the lower. In this particular case, the corrections involved are not in fact very large, so that it is possible to quickly find a value of damping for each curve which is reasonably consistent with all of the data. This has been done for the resonance curves of Fig. 14 with the following results:

Force Level (Relative Magnitude)	Per Cent Critical Damping
4.92	2.8
2.46	2.6
1.00	2.0

As would be expected, the damping is highest at the largest exciting force level and decreases as the dynamic stresses decrease.

Because of the various difficulties mentioned above, the accuracy of the damping determination cannot be considered to be very high. All things considered, the above values seem to fit all of the available data. It would perhaps be best to conclude that for this test the damping was between 2 and 3 per cent of critical.

As mentioned above, these values of damping were rather lower than had been anticipated. Considering the nature of the tower, however, and the fact that the stress levels were very low, with only compressive stresses involved, such values are perhaps not inconsistent with other investigations.

One interesting experimental investigation which came to our attention during the project was reported by Scruton and Harding*. Free vibration decay tests were made on a 425 ft. high reinforced concrete chimney. The stack was of circular section 36 ft. dia. at the base, and decreased linearly from a height of 58 ft. to a dia. of 24 ft. at 412 ft. The wall thickness varied from 18 in. at the base to 5 in. at the top. The bottom half of the chimney

* Scruton, C., and Harding, D. A., "Measurement of the Structural Damping of a Reinforced Concrete Chimney Stack at Ferrybridge "B" Power Station", National Physical Laboratory, NPL/Aero/323/1957.

was brick-lined at the time of the test. The chimney was excited by firing rockets from the top and motions were measured with crystal accelerometers. The results of three tests are as follows:

Max. Ampl. inch	Freq. cyc/sec	Per Cent critical damping
0.22	0.62	0.8
0.40	0.61	1.0
0.56	0.61	1.0

This damping of 1% is of course considerably lower than has been commonly thought of in connection with concrete structures. The low stress level and the absence of energy-dissipating joints will no doubt explain the comparison between this value and the higher values obtained for some other types of concrete structures. It should be realized, however, that experimental studies in this field have been few and far between, and that the amount of reliable test data available is far from satisfactory. The low values of damping found in the above tests certainly indicates that for certain types of structures dynamic effects may play an even more important role than had been hitherto appreciated. It will evidently be important to carry out many additional investigations of this kind to extend our knowledge of this important area of structural dynamics.

Acknowledgements. The Encino Dam Intake Tower vibration test was a cooperative effort involving contributions from many people. The arrangements for making the Intake Tower available for test were made by Mr. S. B. Nelson, Chief Engineer of Water Works and Assistant Manager, Department of Water and Power, City of Los Angeles. Mr. H. B. Hemborg of the Department of Water and Power was of great assistance in working out the details of the test. Construction operations at the test site were under the general supervision of the Kirst Construction Company, whose cooperation is appreciated. Mr. J. F. Meehan, Research Director, Schoolhouse Section, State of California, Department of Public Works, Division of Architecture, who has been representing the State Division of Architecture throughout the development of the vibration exciter system, took an active interest in the present test project. Mr. W. K. Cloud, Chief of the Seismological Field Survey, U.S. Coast and Geodetic Survey, not only made available the Sprengnether portable vibration seismograph, but carried out the operation of the instrument during the tests as well. Transportation of the equipment back and forth between Pasadena and Encino, and the difficult job of installation of the vibration exciter on top of the intake tower was taken over by the California Institute of Technology Physical Plant facilities, Mr. Wesley Hertenstein, Director, with the assistance of Mr. A. S. Hicks. Assistance with the mounting details of the vibration exciter unit was given by Mr. D. W. Laird and Mr. F. L. MacDonald of the C. I. T. Mechanical Engineering Shop, and Mr. R. J. Williams of the C. I. T. Dynamics Laboratory assisted in the installation and calibration of the instrumentation. A number of graduate students in the Division of Engineering at C. I. T. rendered valuable service in the collecting of data, etc., including A. J. Chandrasekaran, H. C. Merchant, and L. S. Srivastava. The studies of the tower foundation conditions were made by Professor F. J. Converse, of the Converse Foundation Engineering Company. The development of the vibration exciter system is under the general supervision of a committee of

the Earthquake Engineering Research Institute, composed of Professor L. S. Jacobsen, Stanford University, Professor R. W. Clough, University of California, Berkeley, and Professors G. W. Housner and D. E. Hudson of the California Institute of Technology. The basic mechanical design of the shaking units was carried out at C. I. T. by Professor D. A. Morelli, with the assistance of Mr. R. D. dePencier, and the electrical drive and control system was developed by Professor T. K. Caughey with the assistance of Mr. R. V. Powell.

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Appendix

Foundation Report on Encino Dam Intake Tower

CONVERSE FOUNDATION ENGINEERING COMPANY

126 West Del Mar Blvd.
P. O. Box 2268 p
Pasadena, California

2 February 1961

Dr. George W. Housner
Department of Civil Engineering & Mechanics
California Institute of Technology
1201 East California Blvd.
Pasadena, California

Subject: Borings at Encino Dam and Reservoir

Dear Dr. Housner:

At your request two borings were made near the existing tower at Encino Dam and Reservoir of the Department of Water and Power, in order to determine the character of the rock or soil beneath the tower.

Boring No. 1 was 10 feet south of the tower, starting at Elevation 916.91. The log of the boring is as follows:

0-6"	Very firm silty sand. Probably sandstone partially disintegrated.
6"-1'	Streaks of basaltic rock.
1'-4 1/2'	Very firm sandstone with 15% of cemented gravel and rock up to 3" in size.
4 1/2'-5'	Solid basalt. Very difficult to cut through with a heavy gad and a chopping bucket.

Boring No. 2 was located at 8 1/3 feet north of the tower at Elevation 922.36. The log of the boring is as follows:

0-3 1/2'	Loose silty sand with 5% gravel. Apparently fill.
3 1/2'-6'	Very firm sandstone with cemented gravel up to 3 inches in diameter. Very hard to drill or break up even with a heavy gad and chopping bucket.

Since the elevation of the bottom of the pier is given as 915.91, it is our opinion that the tower rests upon rock.

Respectfully submitted,

CONVERSE FOUNDATION ENGINEERING COMPANY
(signed) Frederick J. Converse)

FJC:ph

Vibration Tests of the Encino Dam Intake Tower

List of Figures

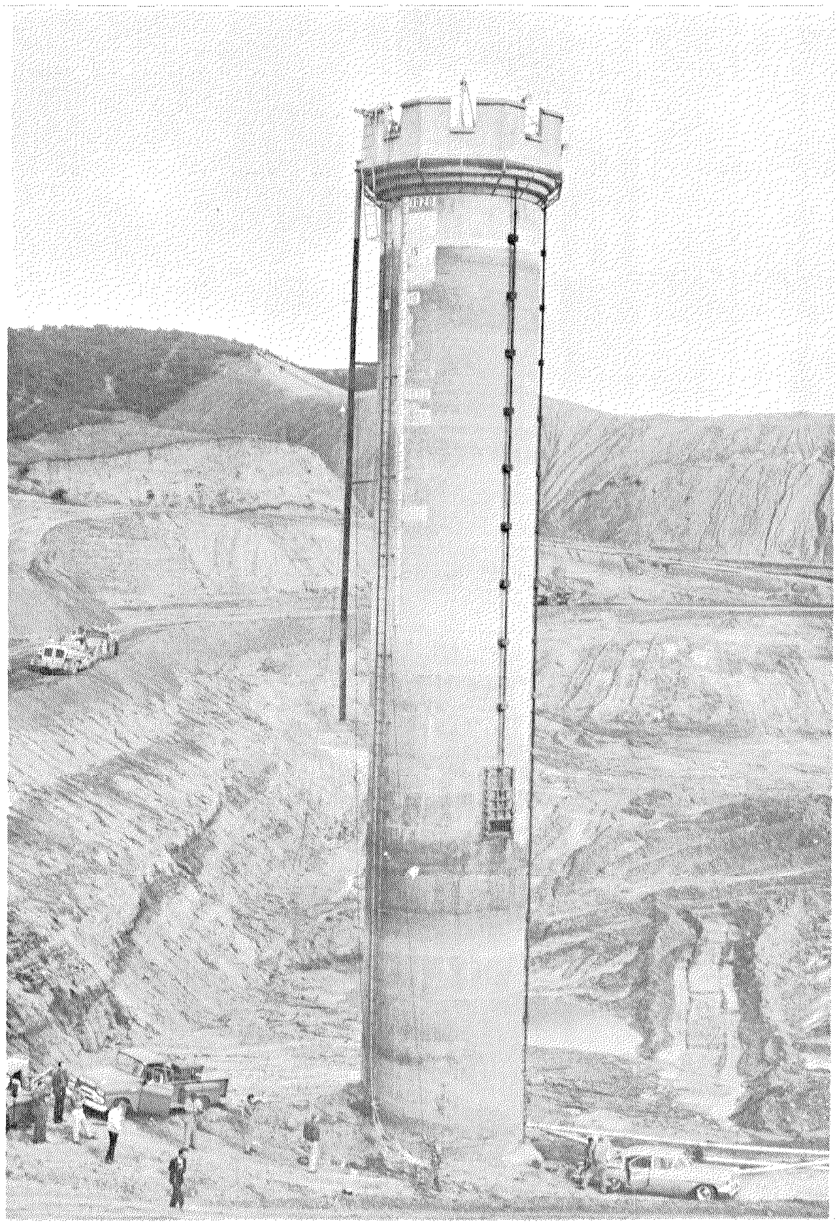


Fig. 1 Encino Dam intake tower - General View.

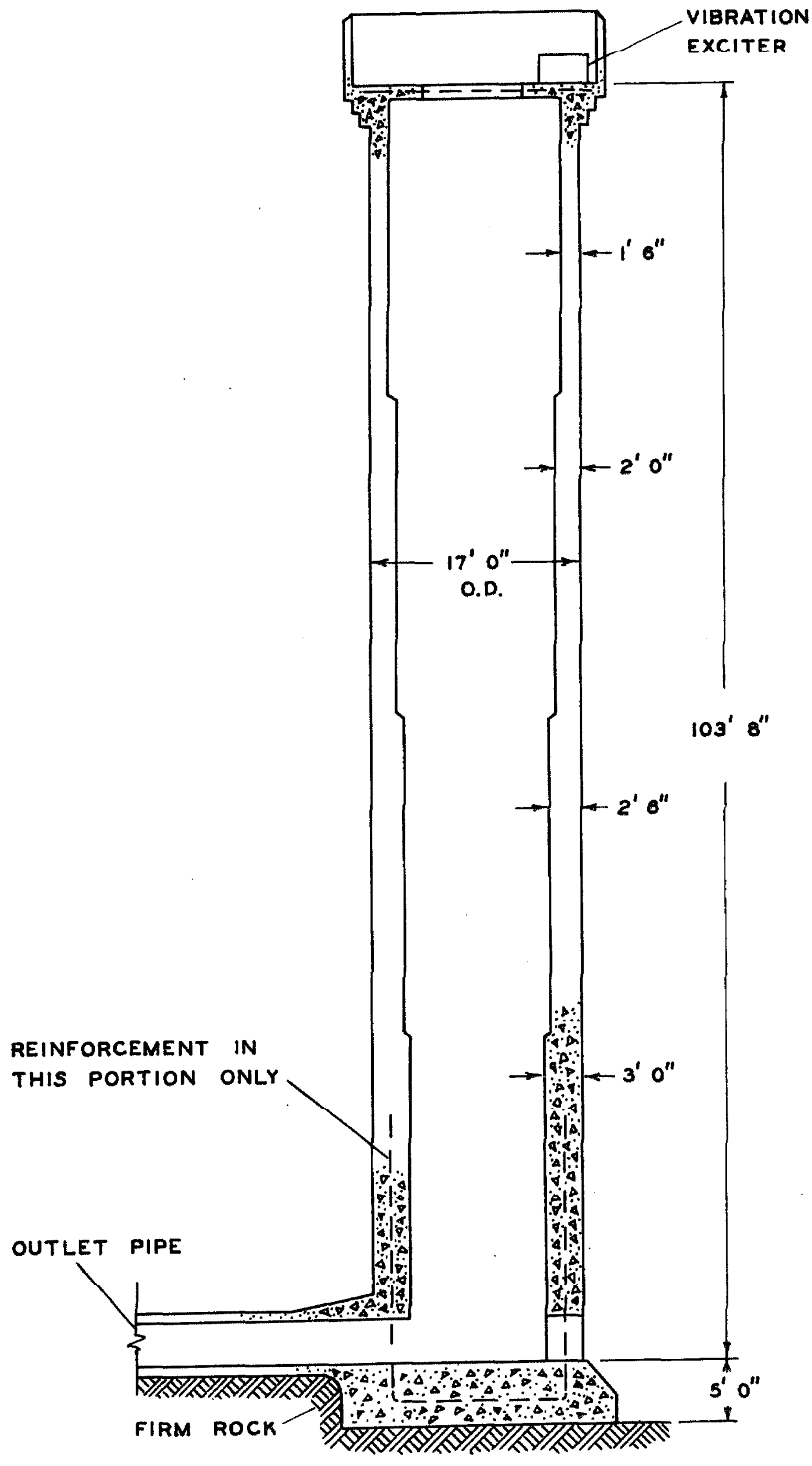


FIG. 2 CONSTRUCTION AND DIMENSIONS OF THE ENCINO DAM INTAKE TOWER

Fig. 3   Site conditions at the Encino Dam intake tower.

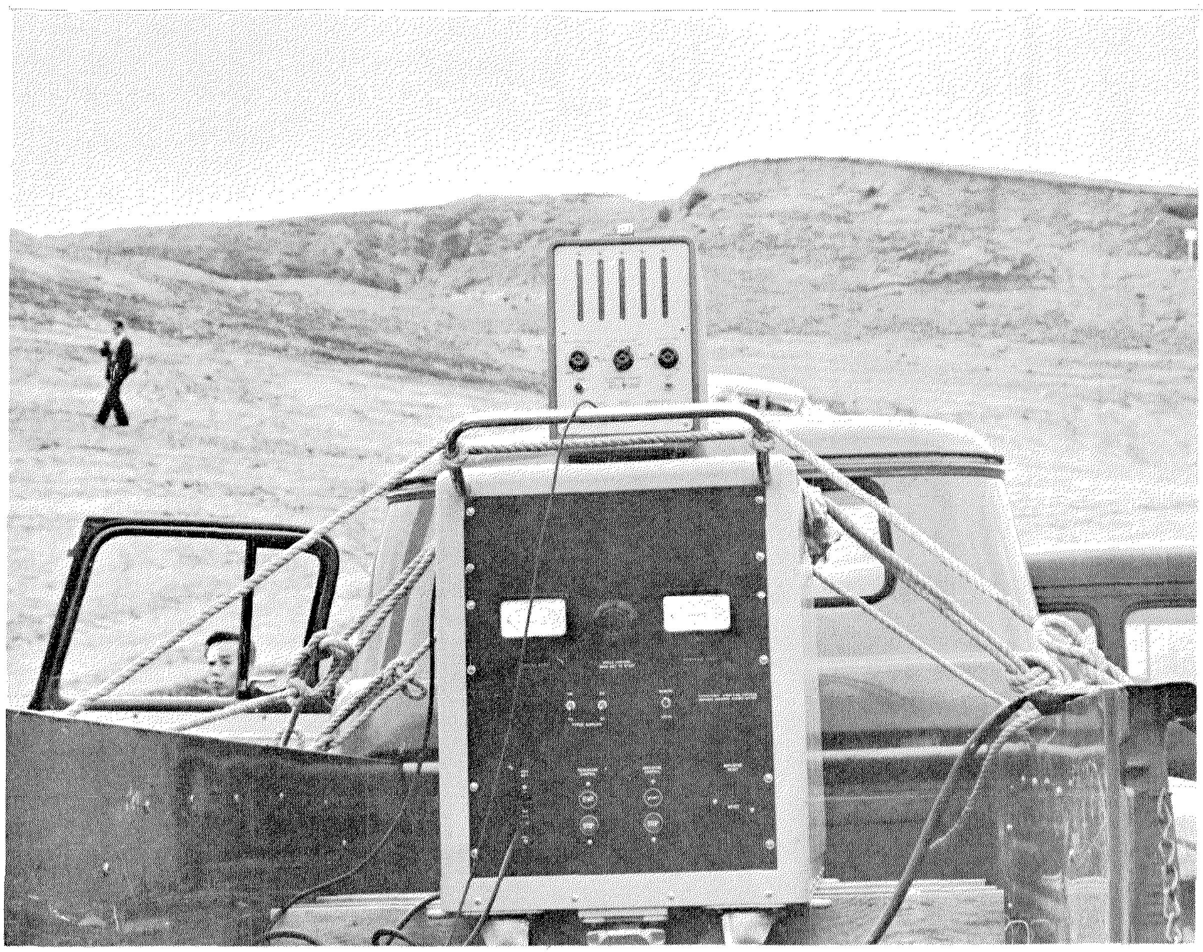


Fig. 4 Speed control console for vibration exciter on shock mount systems.

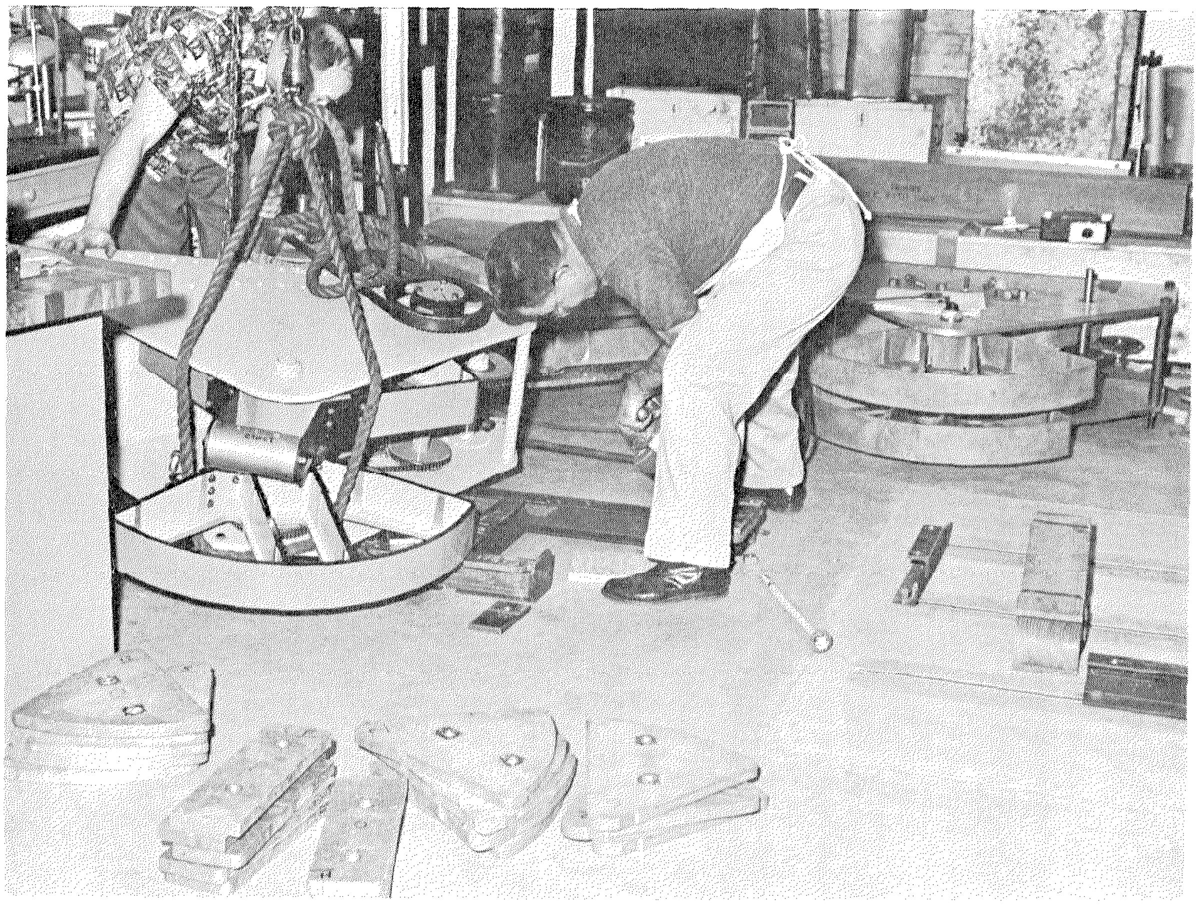


Fig. 5 Vibration exciter unit being installed in laboratory.

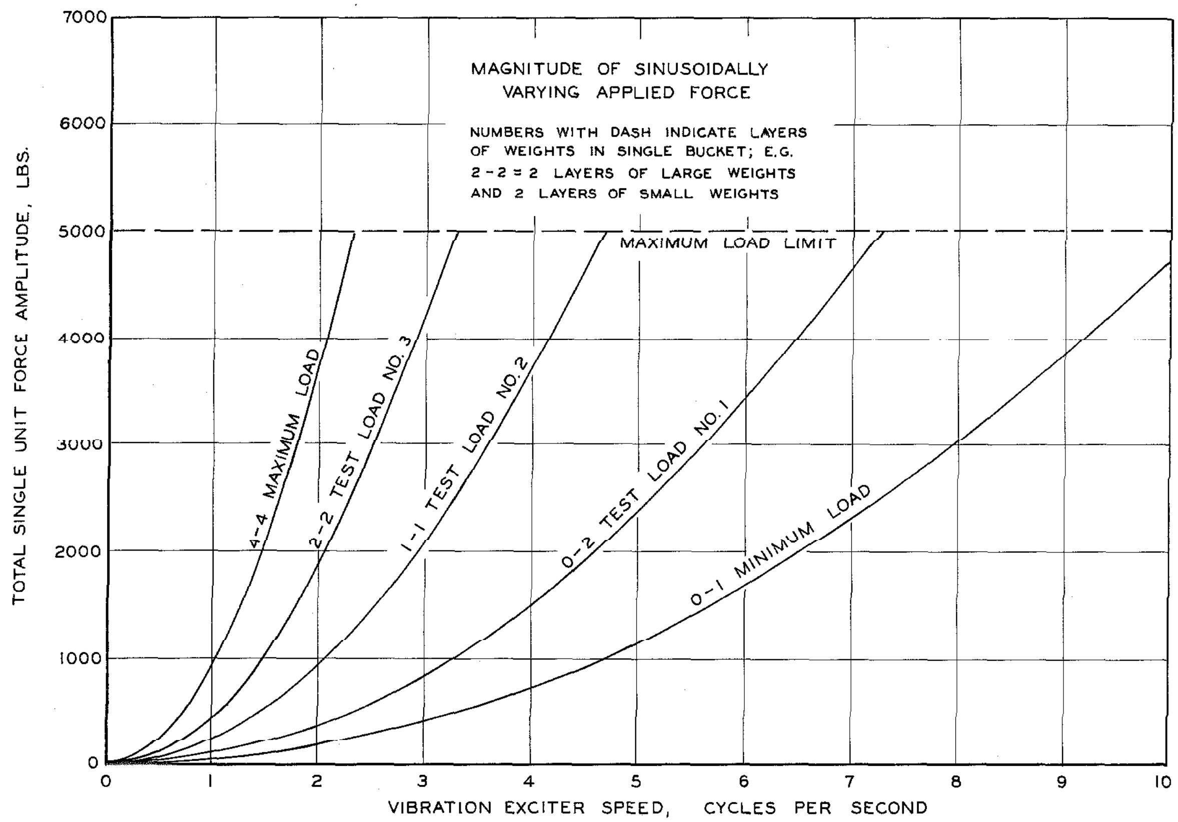


FIG. 6 VIBRATION EXCITER FORCE OUTPUT

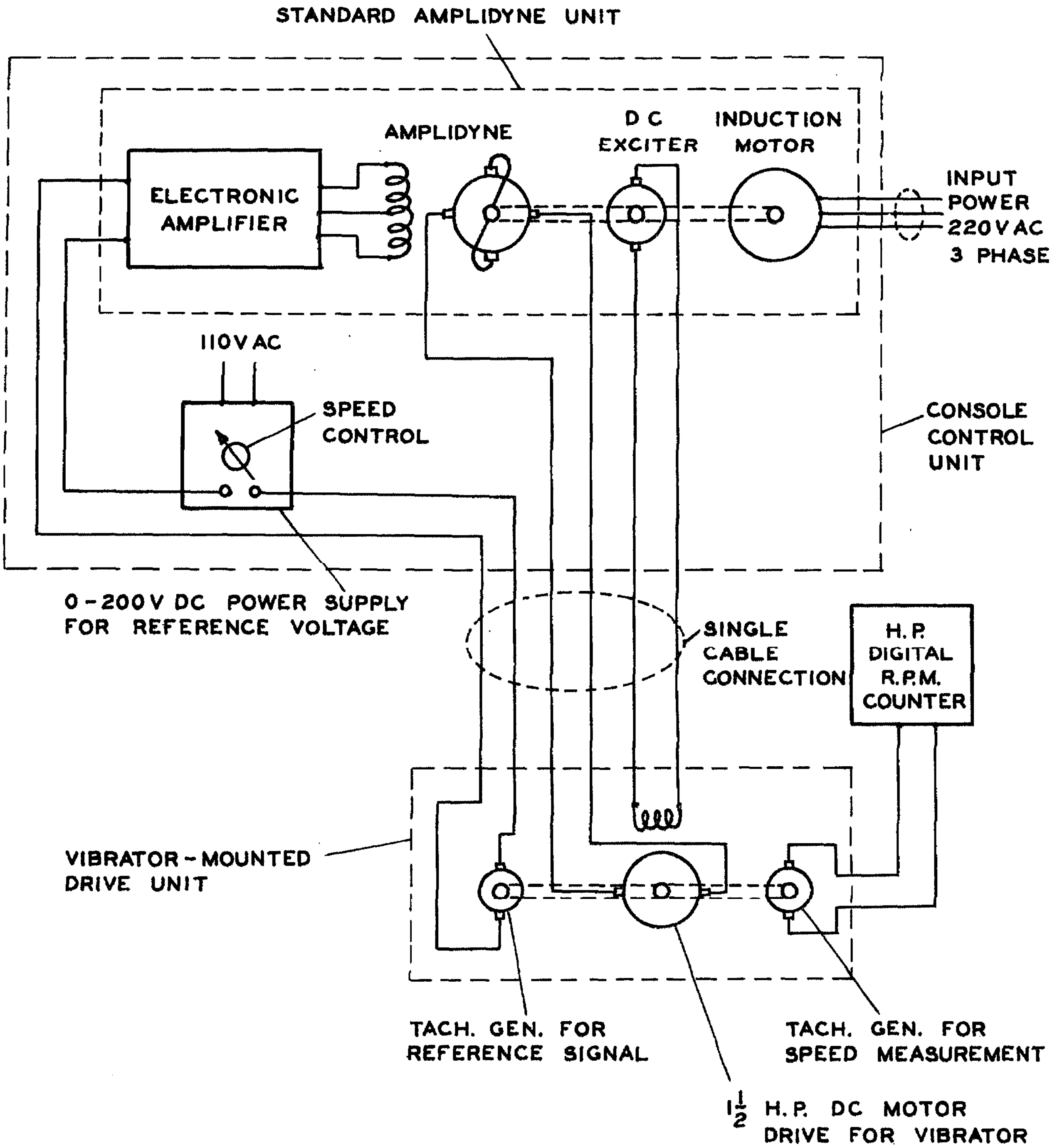


FIG. 7 SCHEMATIC DIAGRAM OF ELECTRICAL SYSTEM FOR VIBRATION EXCITER SPEED CONTROL

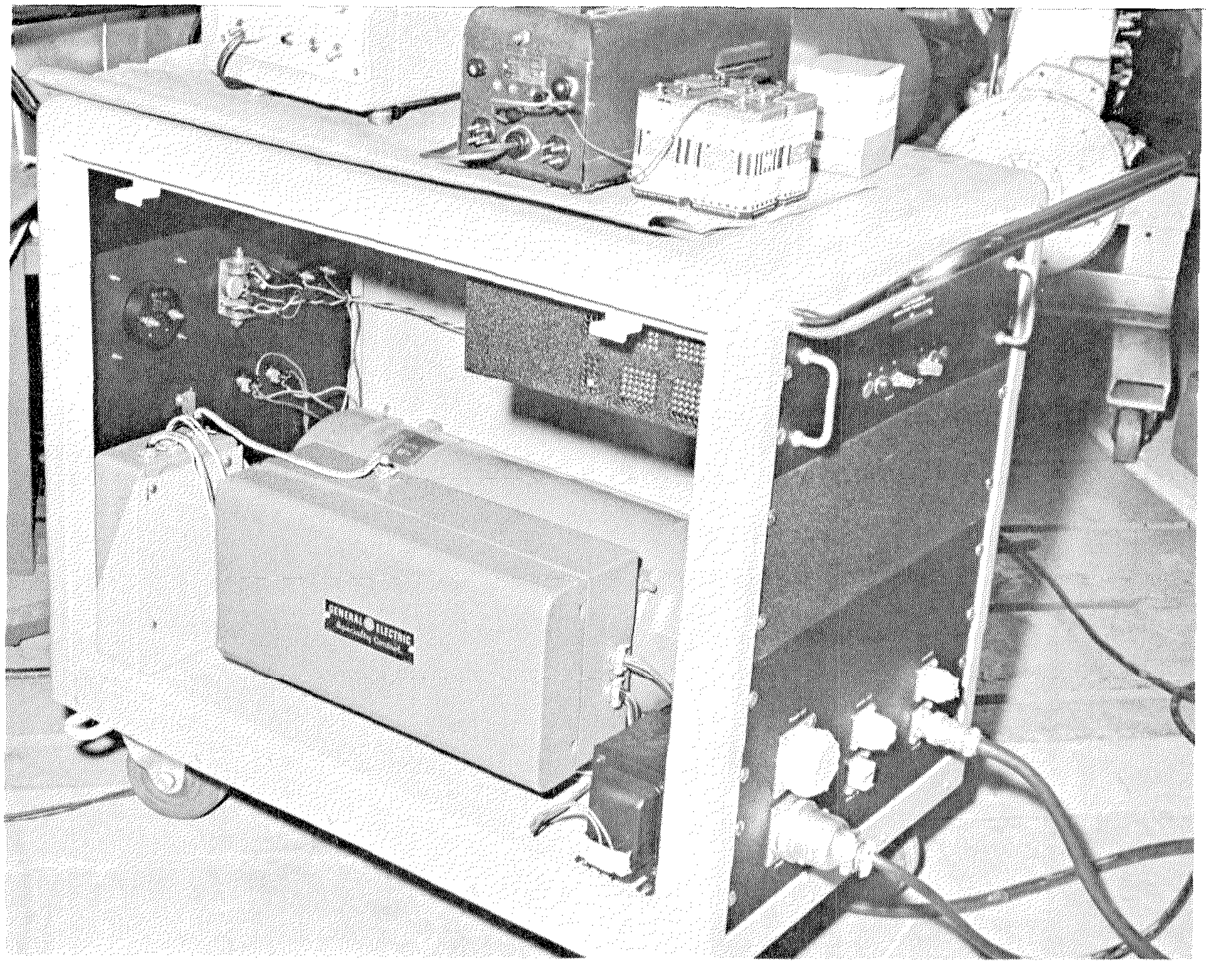


Fig. 8 Interior view of portable speed control console.

Fig. 9 Vibration exciter unit being hoisted to top of tower.

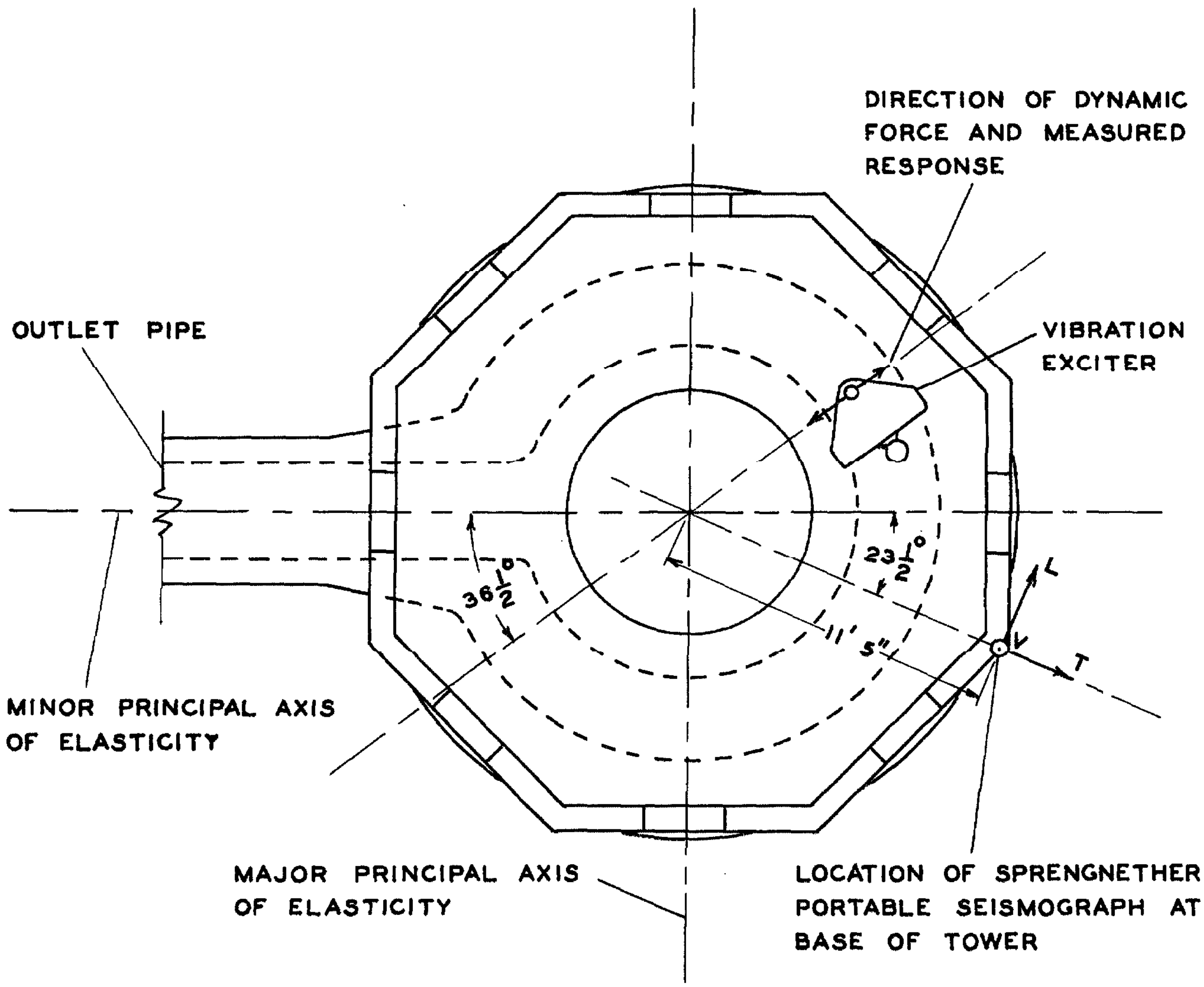


FIG. 10 PLAN VIEW OF TOP OF TOWER SHOWING LOCATION OF VIBRATION EXCITER UNIT

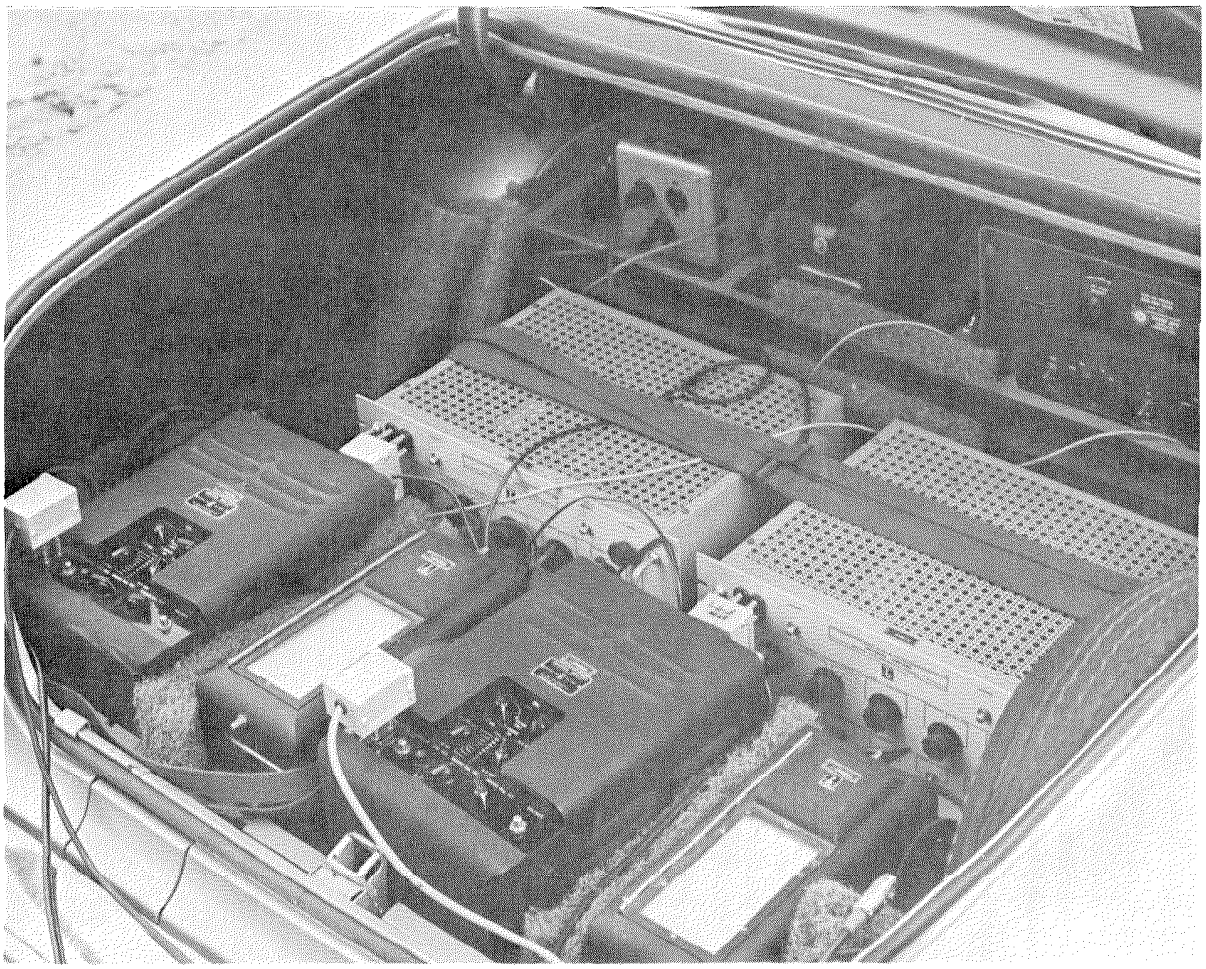


Fig. 11 Accelerometer recording system at the test site.

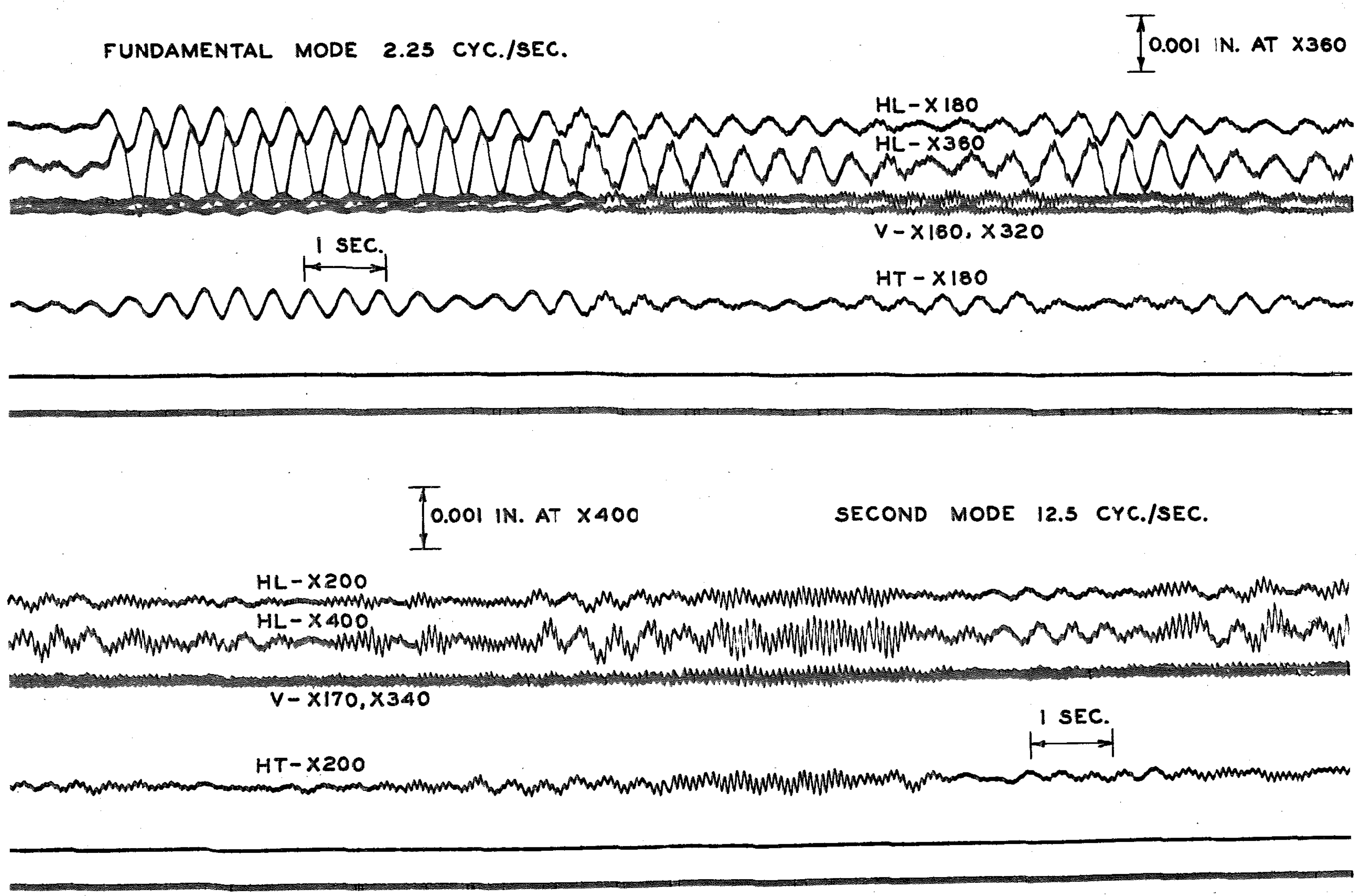
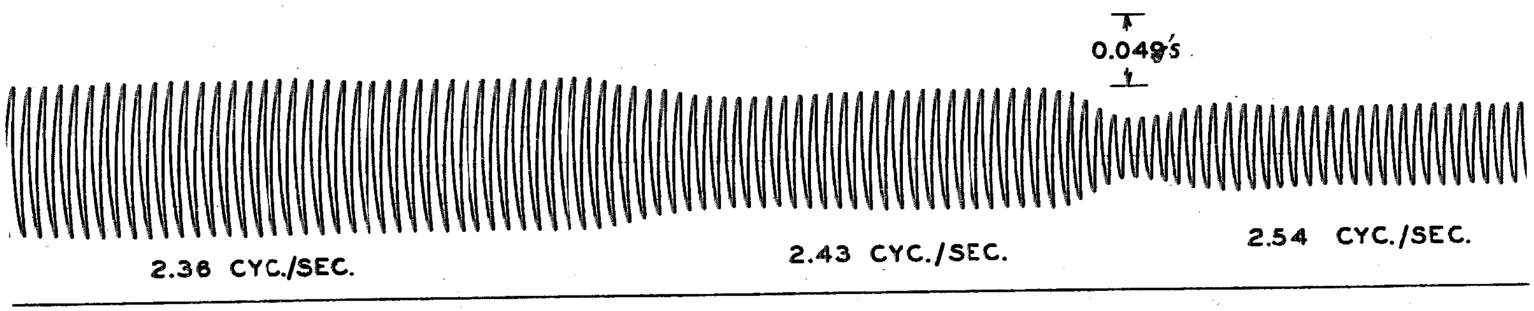


FIG. 12 SAMPLE RECORDS OF WIND-EXCITED TOWER VIBRATIONS



ACCELERATION-TIME CURVES, TOP OF TOWER BELOW FLOOR SLAB
LOAD NO. 3 (2-2) FREQUENCY FROM DIGITAL COUNTER

FIG. 13 SAMPLE RECORD OF TOWER ACCELERATION DURING FORCED VIBRATION RESONANCE TEST. DATA FOR FIG. 14

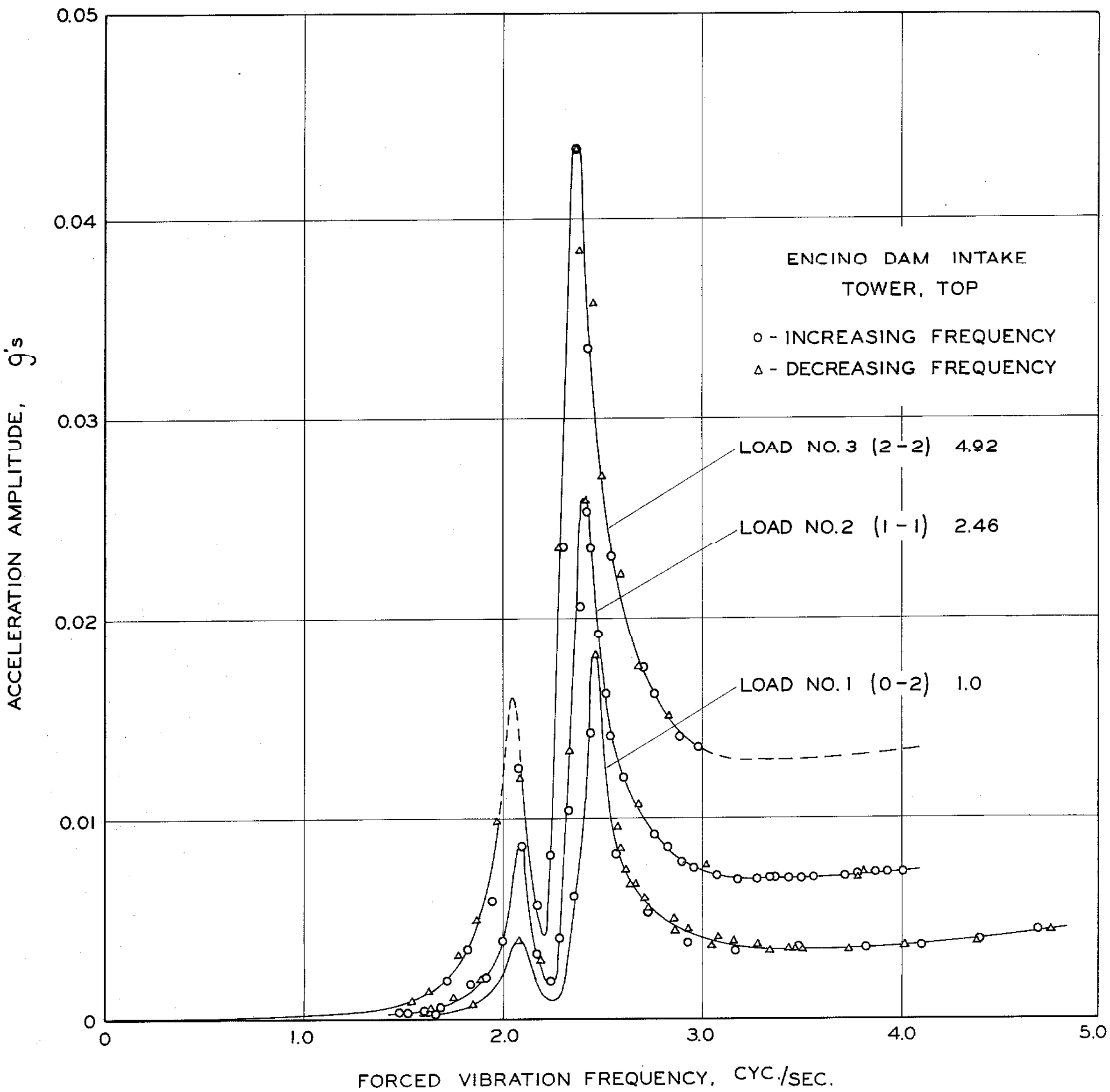


FIG. 14 ACCELERATION RESONANCE CURVES AT TOP OF TOWER

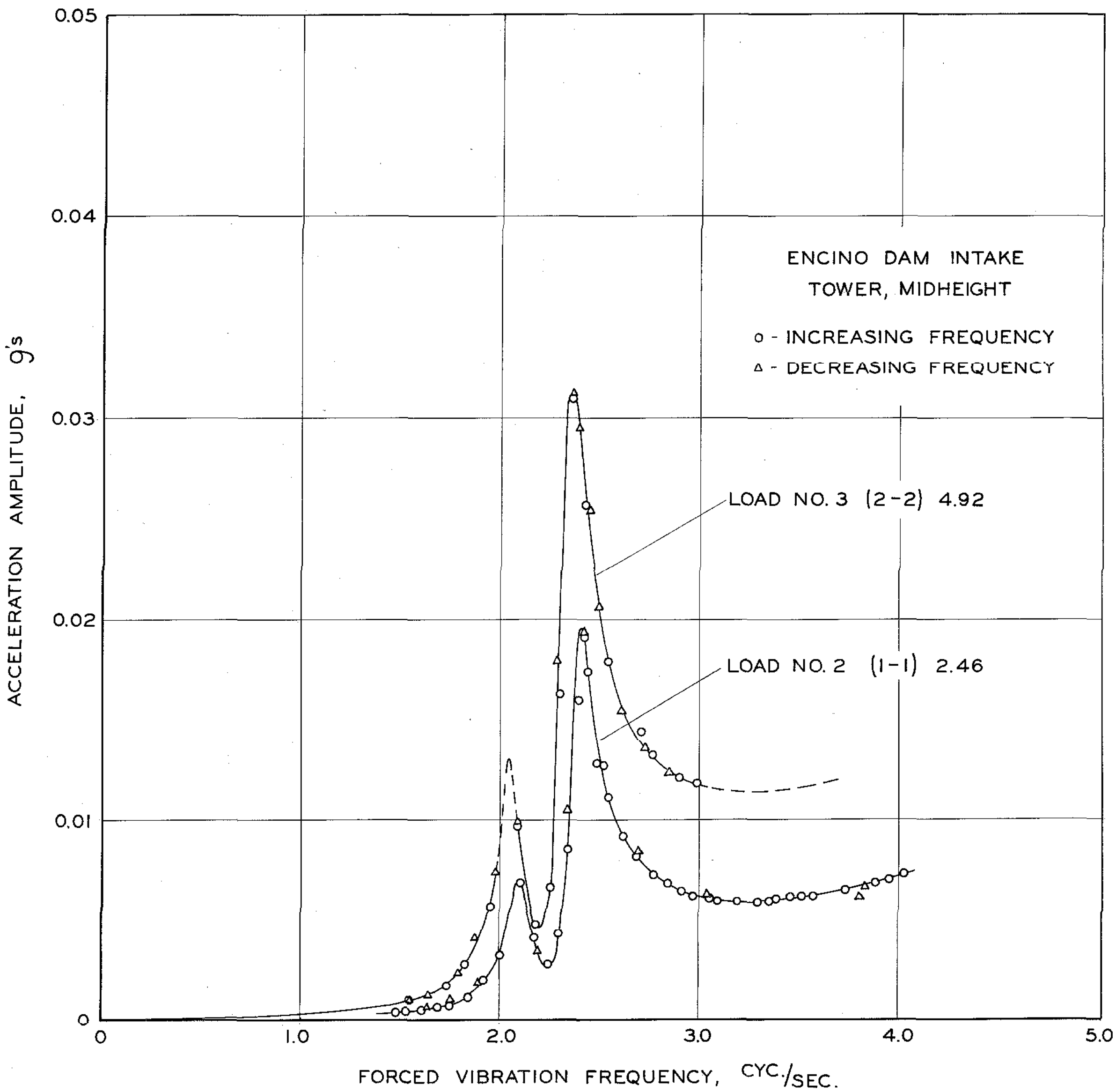


FIG. 15 ACCELERATION RESONANCE CURVES AT MIDHEIGHT OF TOWER

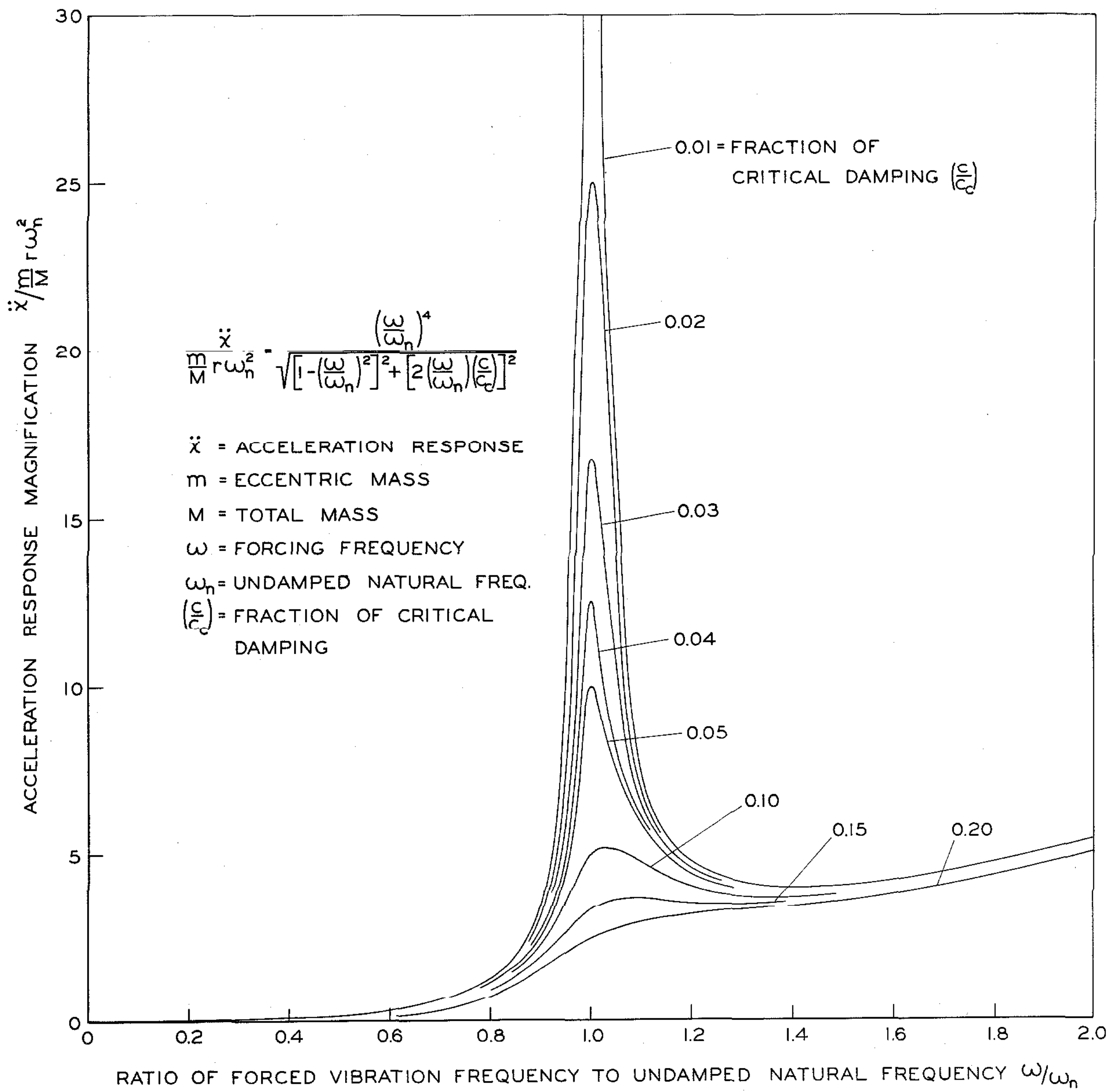


FIG. 16 COMPUTED ACCELERATION RESPONSE RESONANCE CURVES

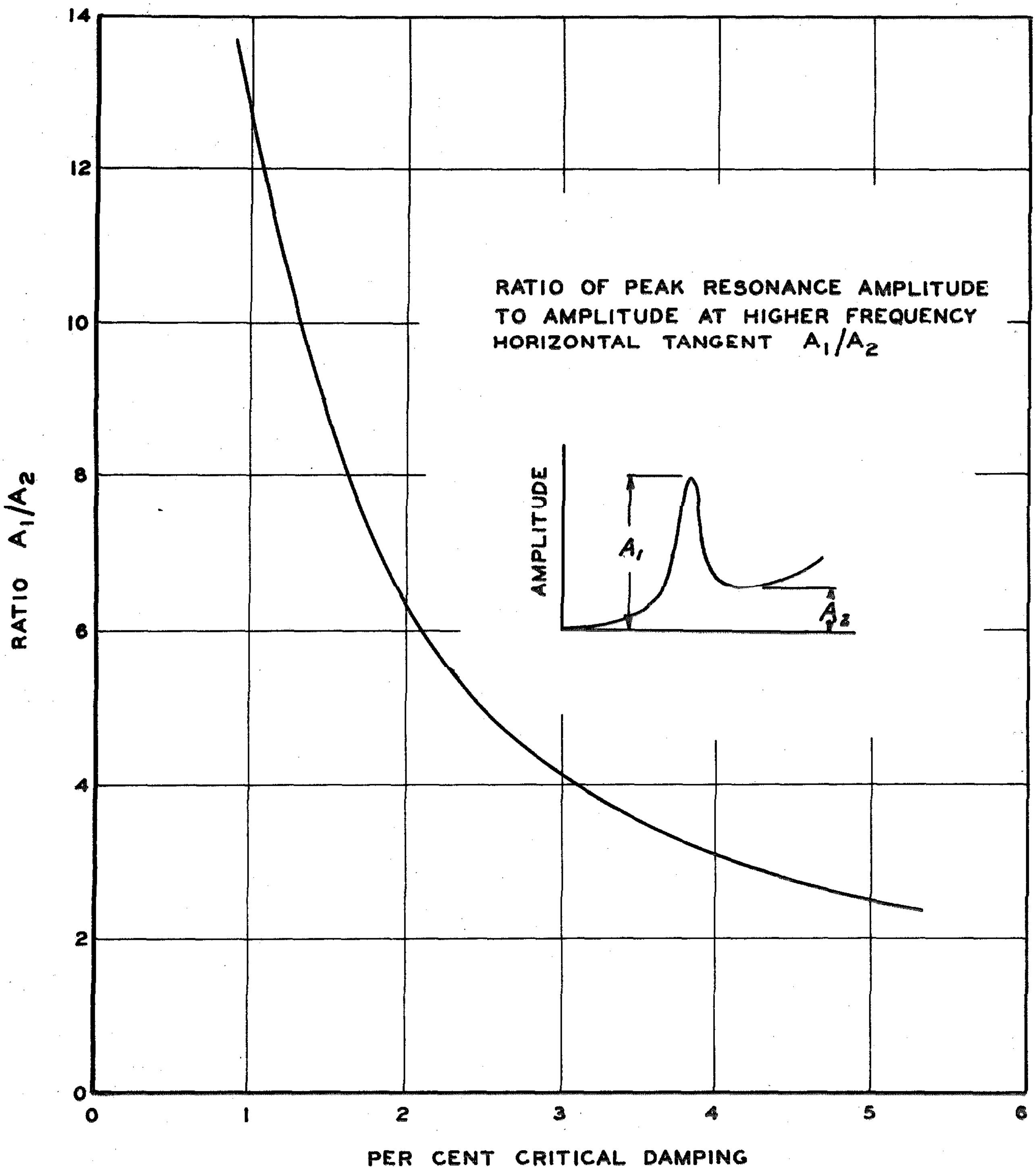


FIG. 17 RATIO OF PEAK AMPLITUDE TO HIGHER FREQUENCY HORIZONTAL SLOPE AMPLITUDE

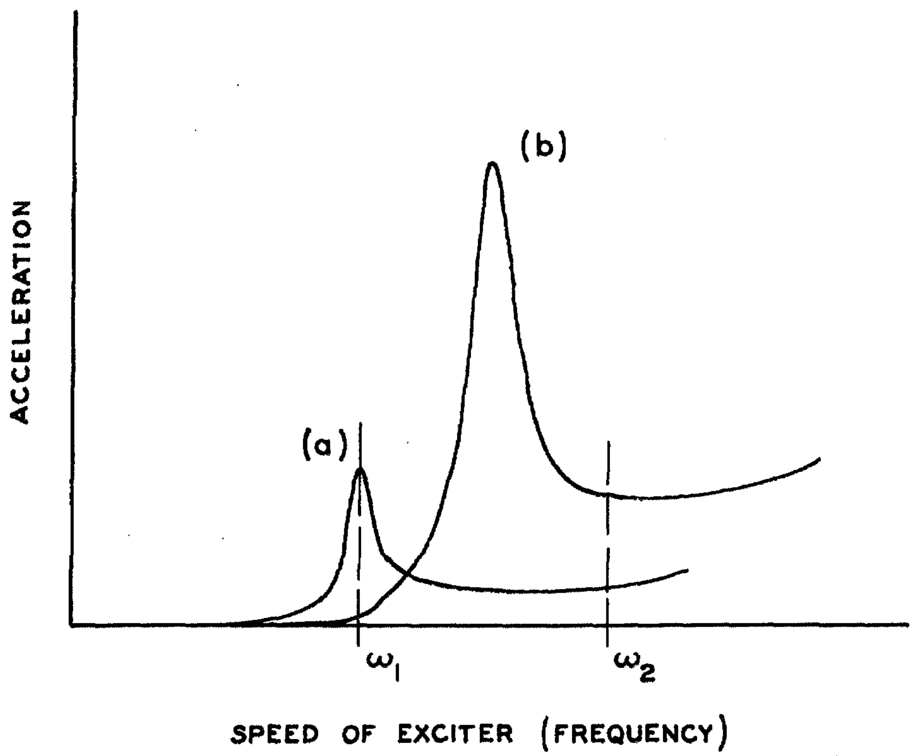


FIG. 18 SCHEMATIC DIAGRAM SHOWING TWO SUPERIMPOSED RESONANCE CURVES